Formation of micro-cracks in $Al_xGa_{1-x}N$ layers: Direct imaging of the defect distribution and strain relaxation correlating spatially, spectrally, and time resolved cathodoluminescence microscopy and micro-Raman spectroscopy

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A series of $Al_xGa_{1-x}N$ layers with different Al-content were comprehensively characterized by spatially-, spectrally- and time-resolved cathodoluminescence microscopy (CL) and micro-Raman spectroscopy.
1 µm thick $Al_xGa_{1-x}N$ layers were grown by molecular beam epitaxy on the top of a 1 µm thick GaN layer using a (0001) sapphire substrate. The Al-content x of the samples determined by X-ray diffraction (XRD) is varied from x = 0.05 to 0.20.
The laterally integrated CL spectra of the different $Al_xGa_{1-x}N$ layers show identical behavior: a high energetic narrow peak P0 dominates the spectra and is accompanied by a weaker broad satellite peak P1. A second additionally broad weak peak P2 is observed in the layer with a higher Al-content of x > 0.15.
Monochromatic CL images (CLI) at the spectral position of the narrow main peak P0 corresponding to the near band gap luminescence from the AlGaN layer shows a homogeneous intensity distribution. The full width at half maximum (FWHM) of this peak increases monotonously from 17 meV for an Al-content of x = 0.05 up to 98 meV for x = 0.2 caused by Al-fluctuations and the inhomogeneous stress distribution.
In contrast, the CLIs of the broad satellite peak P1 are complementary to CLIs of P0 having a strongly localized intensity distribution correlating with structural defects.
Micro-cracks are observed in AlGaN layers with an Al-content of x > 0.15 resulting in a splitting of the main CL line P0. The micro-cracks form a hexagonal network showing well-defined discrete values of the distance between the cracks. The crack areas themselves are the regions of highest integral and peak luminescence intensity, however, the their local CL peak $P0_2$ is blue shifted with respect to the averaged main peak $P0_1$.
Maps of the local CL emission wavelength (CLWI) over an area of 55 x 36µm^2 directly image the lateral fluctuation of the local bandgap, i.e. the local Al-content and strain. Histograms of these CLWI yield quantitatively information of the statistical distribution. While a single Gaussian is obtained for the AlGaN layers without cracks a bimodal distribution is found for the AlGaN layers with micro-cracks: For the strained crack-free areas of an $Al_{0.2}Ga_{0.8}N$ layer we find a mean value of E_{01} = 3.967eV with a standard deviation of σ = 45meV. For the blue-shifted, strain relaxed micro-crack regions a value of E_{02} = 4.001eV and a standard deviation of σ = 25meV is measured corresponding to σ_{Al} = 0.009.
CL spectrum linescans across the cracks visualize a bowing of the local CL emission energy from $P0_1$ to $P0_2$ reaching its maximum at the very crack position. The maximum shift of emission energy increases with increasing crack distance. This shift of the CL emission energy directly correlates with the strain profile between the micro-cracks. To correlate optical and structural properties the stress distribution was independently measured by micro-Raman spectroscopy and is compared with theoretical calculations of the strain relaxation.
The carrier dynamics in the strain region as well as at the cracks of the AlGaN layer was investigated using spatially-spectrally-time-resolved CL microscopy.

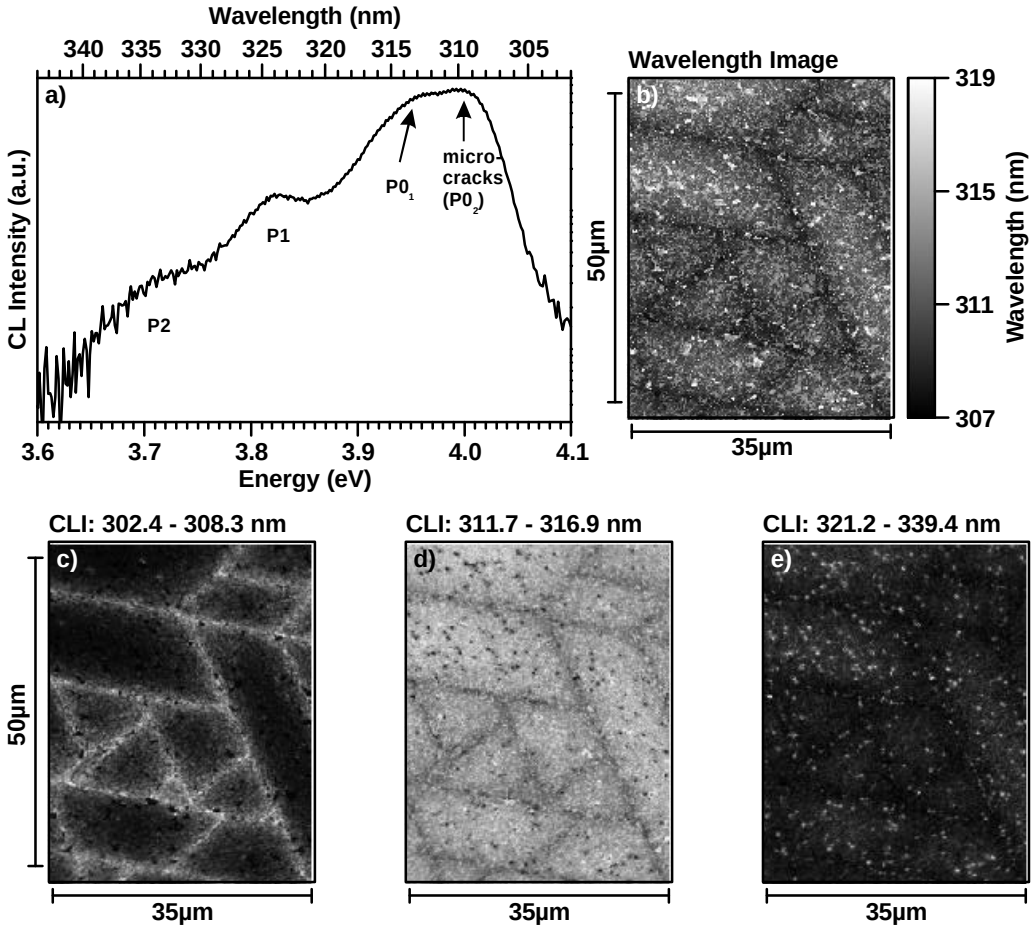

Fig. 1: a) Laterally integrated CL spectrum, b) CL wavelength image and normalized monochromatic CL images (CLI) c) from the luminescence of the strain relaxed micro-cracks ($P0_2$: 302.4 - 308.3 nm), d) from the tensile strain layer ($P0,P0_1$: 311.7 - 316.9 nm) and e) from the defects (P1 + P2: 321.2 - 339.4 nm) of a 1µm thick $Al_{0.2}Ga_{0.8}N$ layer at low temperature (T = 5K).

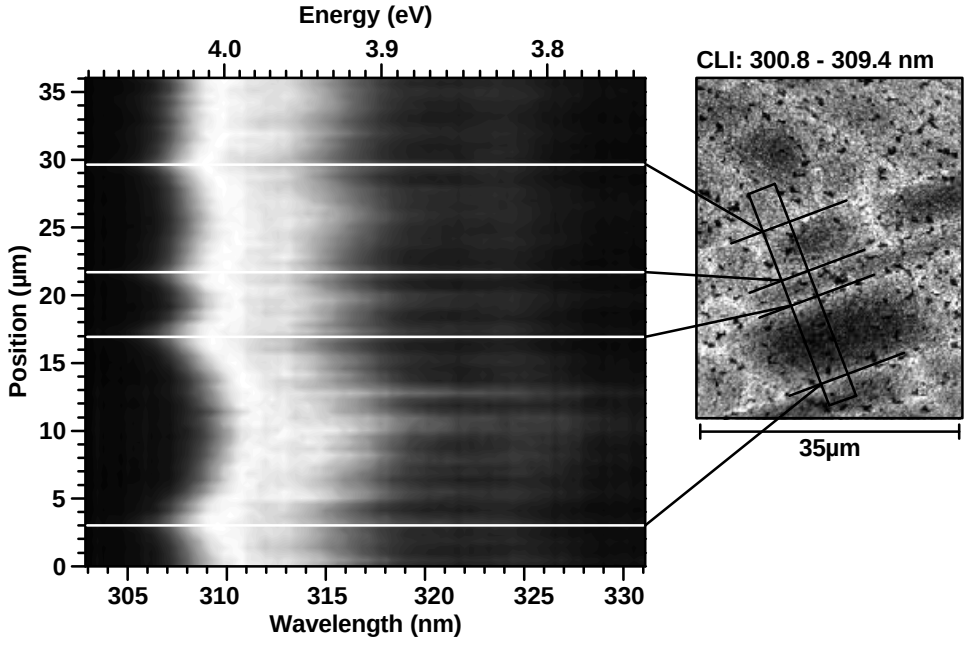

Fig. 2: CL spectrum linescans across 4 micro-cracks on 1µm thick $Al_{0.2}Ga_{0.8}N$ layer